System Design for the North Atlantic Link

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The purpose of this paper is to examine the design and performance of the North Atlantic link, including consideration of factors governing the choice of features, a description of the operational design of the facility, and an outline of those measures available for future application in the event that faults or aging require corrective action.

DESCRIPTION OF LINK

That portion of the transatlantic system[1] which connects Newfoundland and Scotland consists of a physical 4-wire, repeatered, undersea link of Bell Telephone Laboratories design, with appropriate terminal and power feeding equipment in cable stations at Clarenville and at Oban.

The various elements comprising the link are shown in block form in Fig. 1. The termination points at each end of the link are the Group Distributing Frames (GDF), where the working channels are brought down in three groups to the nominal group frequency band 60–108 kc. At the west end, this point provides the interconnection between the North Atlantic and the Newfoundland-Nova Scotia links. At the east end, it is the common point between the North Atlantic link and the standard British toll plant over which the circuits are extended to London.

Two separate coaxial cables connect Clarenville with Oban, one handling east-to-west transmission, the other west-to-east. Each is about 1,940 nautical miles long. A total of 102 repeaters are installed in the two cables, at nominal intervals of 37.5 nautical miles. The cables also contain a number of simple undersea equalizers which are needed to bring system performance within the specified objectives.

The working spectrum of each cable extends from 20 to 164 kc, pro-

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* Bell Telephone Laboratories.

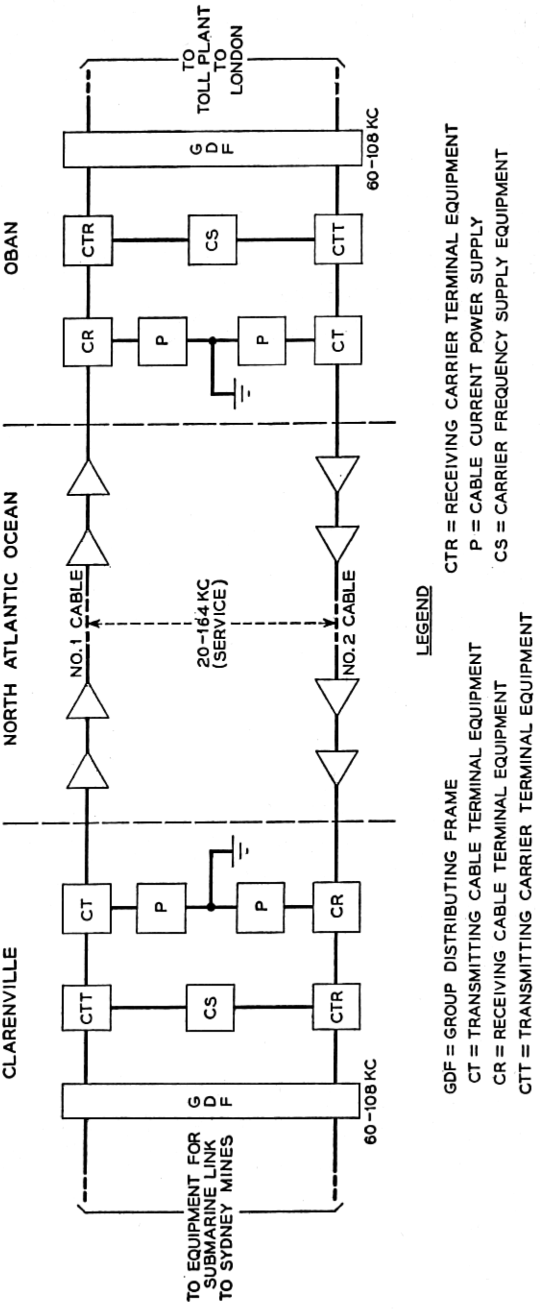

Fig. 1 — Schematic — North Atlantic link.

viding for 36 4-kc voice message channels. Below this band are assigned the telephone (speaker) and telegraph (printer) circuits needed for maintenance and administration of the facility. Above the working band, between 167 and 174 kc, are the crystal frequencies, which permit evaluation of the performance of each repeater individually from the shore stations.

The signal complex carried by the cables is derived in the carrier terminals from the signals on the individual voice frequency circuits by conventional frequency division techniques such as are employed in the Bell System types J, K and L broadband carrier systems manufactured by the Western Electric Company. (See Fig. 2.) These signals are applied to the cable through a transmitting amplifier which provides necessary gain and protects the undersea repeaters against harmful overloads. At the incoming end of each cable, a receiving amplifier provides gain and permits level adjustment.

Shore equalizers next to the transmitting and receiving amplifiers insert fixed shapes for cable length and level compensation. Adjustable units provide for equalization of the system against seasonal temperature changes on the ocean bed, and some aging.

The power equipment at each cable station includes (a) regular primary power with Diesel standby, (b) rotary machines for driving the cable current supplies, with battery standby, (c) battery plants for supplying the carrier terminal bays, and (d) last but by no means least in complexity, the cable current supplies themselves. These latter furnish regulated direct current to a series loop consisting of the central conductors of the two cables, with their repeaters. A power system ground is provided at the midpoint of the cable current supply at each cable station.

FACTORS AFFECTING SYSTEM DESIGN

General

A repeatered submarine cable system differs from the land-wire type of carrier system in two major respects. First, the cost of repairing a fault, and of the concurrent out-of-service time, is so great as to put an enormous premium on integrity of all the elements in the system and on proper safeguards in the system against shore-end induced faults. Second, once such a system is resting on the sea-bottom it is accessible for adjustment only at its ends. These two restrictions naturally had a profound influence on the design of the North Atlantic link.

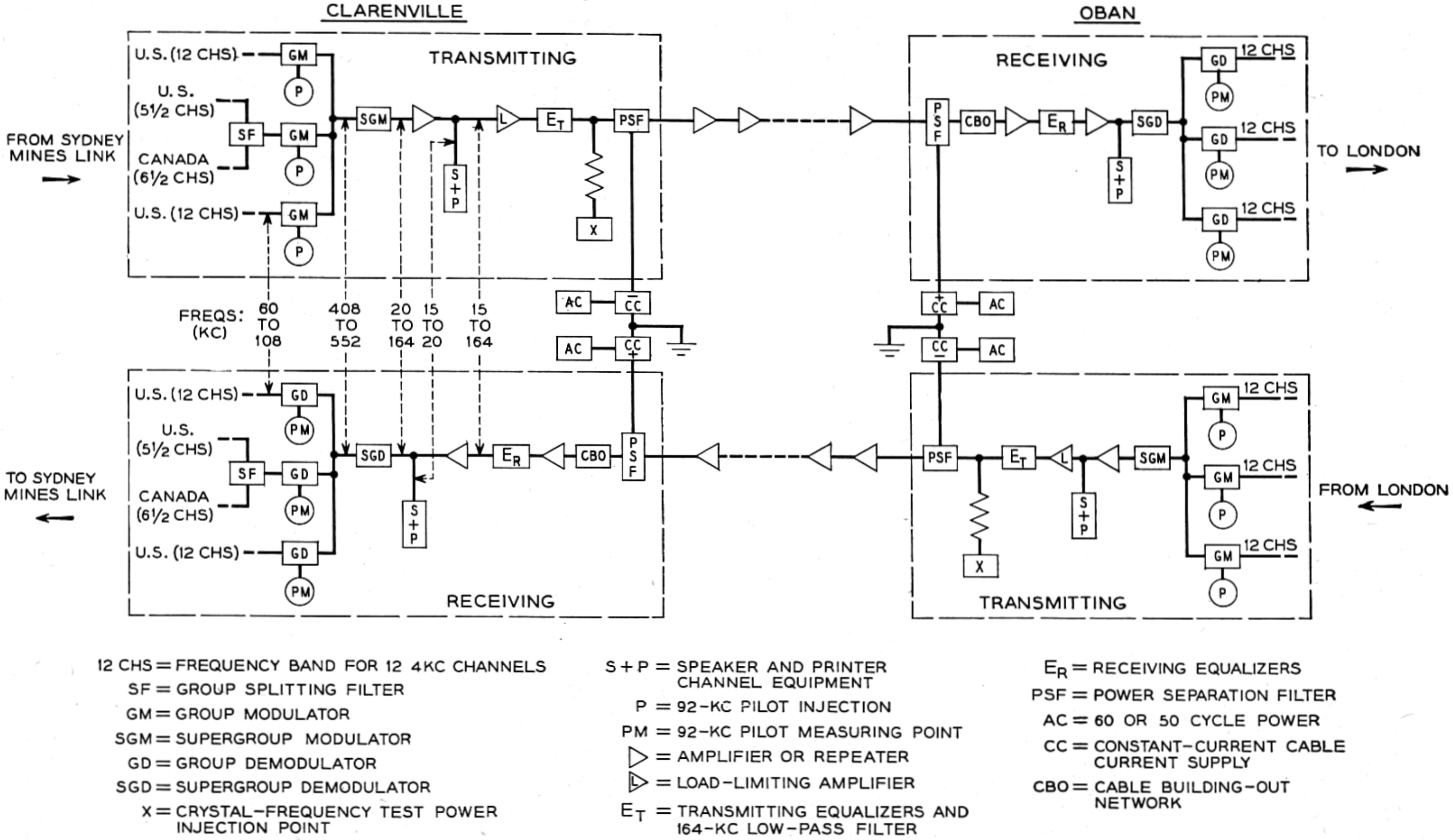

Fig. 2 — Block schematic of terminals — North Atlantic link.

Proven Integrity

Assurance of reliability dictated use of elements whose integrity had actually been proved by successful prior experience in the laboratory or in the Bell System. This resulted in adoption of a coaxial cable structure explored by the Laboratories soon after the war, field tested in the Bahamas area in 1948 and applied commercially on the USAF Missile Test Range project[13] in 1953. It also resulted in specification of a basic flexible repeater design which had been under test in the Laboratories since before the war and had been in use on the Key West-Havana submarine cable telephone system[4] since 1950.

Cable

The cable adopted was the largest which had actually been successfully laid in deep water, and its size afforded an important benefit in the form of reduced unit attenuation. The structure and characteristics of this cable are covered in detail in a companion paper.[2] Suffice it to point out here that by its adoption for the North Atlantic link, there were specified for the system designers (a) the attenuation characteristic of the transmission medium, (b) the influence on this of the pressure and temperature environments, (c) the unit contribution of the cable to the resistance of the power loop, and (d) the impedances faced by the repeaters.

Repeater

The adaptation[3] of the basic Key West-Havana repeater design to the present project likewise presented the system designers with certain restrictions. Most important, the space and form of the long, tubular structure limited the size of the high voltage capacitors in the power separation filters, and thus their voltage rating, to the extent that this determined the maximum permissible number of repeaters. Likewise the performance of the repeater circuit was at least partially defined because of several factors. One was the effect of the physical shape on parasitic capacitances in the circuit, which in turn reacted on the feedback and hence on modulation performance, gain-bandwidth and the aging characteristic. Use of the Key West-Havana electron tube influenced the above factors and also tended to fix the input noise figure and load capacity.

System Design

In similar respects, the principle of proven integrity reacted into the broad consideration of system design. For instance, in a long system having many repeaters in tandem, automatic gain control (gain regulation) in the repeaters provides an ideal method for minimizing the amount of the total system margin which must be allocated to environmental loss variations. However, this would have required adoption of elements of unproved integrity which might have increased the probability of system failure. So the more simple and reliable alternative was adopted — fixed gain repeaters with built-in system margins.

System Inaccessibility

The inaccessibility of the undersea system for periodic or seasonal adjustment and the decision to avoid automatic gain regulation were major factors in the allocation of system margins between undersea and shore locations. To avoid wasting such a valuable commodity as margin, required the most careful consideration of means of trimming the system during laying. Equalization for control of misalignment in the undersea link is a function of the match between cable attenuation and repeater gain. Generally speaking, these are fixed at the factory. Very small unit deviations from gain and loss objectives could well add to an impressive total in a 3,200-db system. Accordingly, it was necessary to plan for periodic adjustment of cable length during laying, and where necessary, insertion of simple mop-up undersea equalizers at the adjustment points.

DESIGN OF HIGH-FREQUENCY LINE

Terminology

The high-frequency line, as the term is used here, includes the cable, the undersea repeaters, the undersea equalizers, and the shore-station power separation filters, transmitting and line-frequency receiving amplifiers, and associated equalizers.

Repeater Spacing and System Bandwidth

As in most transmission media, the attenuation of the cable increases with increasing frequency. Hence the greater the bandwidth of the system, the greater the number of repeaters needed.

In this system, powered only from its ends, the maximum permissible number of repeaters and thus the repeater spacing is determined by a dc voltage limitation, as explained in a later section.

With the repeater spacing fixed, and the type of cable fixed, the required repeater gain versus frequency is known to the degree of accuracy that the cable attenuation is known. The frequency band which can be utilized then depends on repeater design considerations, including gain-bandwidth limitations, signal power capacity and signal-to-noise requirements.

The early studies of this transatlantic system were based on "scaling up" the Havana-Key West system.[4] In these studies, consideration was given to extending the band upward as far as possible by using compandors[5] on the top channels, thus lightening the signal-to-noise requirements on these channels by some 15 db provided they are restricted to message telephone service.

As the repeater design was worked out in detail, however, it became evident that a rather sharp upper frequency limit existed. This resulted from the parasitic capacitances imposed by the size and shape of the flexible repeater, the degree of precision required in matching repeater gain to cable loss in such a long system, and the feedback requirements as related to the requirement of at least 20 years' life.

These limitations resulted in the decision to develop a system with 36 channels of 4-kc carrier spacing, utilizing the frequency band from 20 to 164 kilocycles per second.

Signal-to-Noise Design

Scaling-up of Key West-Havana System

The length of the North Atlantic cable was to be about 16 times that of the Havana-Key West system. The number of channels was to be increased as much as practicable. The length increase entailed an increased power voltage to ground on the end repeaters. Increase in length and in number of channels entailed increased precision in control of variations in cable and repeaters. Work on these and other aspects was carried on concurrently, to determine the basic parameters of the extended system.

Increasing cable size decreases both the attenuation and the dc resistance, and in turn the voltage to ground on the end repeaters. It was soon decided that the largest cable size which could be safely adopted was the one used in the Bahamas tests. This has a center-conductor sea-bottom resistance of about 2.38 ohms per nautical mile. It consumes about 28 per cent of the total potential drop in cable plus repeaters.

Number of Repeaters

As indicated earlier, the factor which emerged as controlling the number of repeaters was the dc voltage to ground on the end repeaters. Considerations which entered into this were: voltage which blocking capacitors could safely withstand over a life of at least 20 years; voltage which other repeater elements such as connecting tapes between compartments could safely hold without danger of breakdown or corona noise; initial power potential and possible need for increasing dc cable current later in life to combat repeater aging; allowance for repair repeaters; and a reasonable allowance for increased power potential to offset adverse earth potential.

Let R = dc resistance of center conductor (ohms/nautical mile)
L = length of one cable* (nautical miles)
E_{rep} = voltage drop across one repeater at current I
I = ultimate (maximum) line current (amperes)
N = ultimate number of submerged repeaters, in terms of equivalent regular repeaters
n = allowance for repair repeaters, in terms of number of regular submerged repeaters using up same voltage drop.
E_m = maximum voltage to ground at shore-end repeaters at end of life, and in absence of earth potential.
S = spacing of working regular repeaters (nautical miles)

Then for the ultimate condition

$$2E_m = LIR - 2SIR + NE_{rep} \tag{1}$$

in which the term $2SIR$ accounts for the sum of the cable voltage drops on the two shore-end cable sections; the sum of their lengths is assumed, for simplicity, to equal $2S$. This equation also neglects a small allowance (less than 0.6 volt per mile) for the voltage drop in cable added to the system during repair operations. Also

$$S(N - n + 1) = L \tag{2}$$

because the repeater spacing is determined by the number of working regular repeaters. From (1) and (2),

$$2E_m = LIR + NE_{rep} - 2LIR/(N - n + 1) \tag{3}$$

The allowance n for repair repeaters was determined after studies of cable fault records of transoceanic telegraph cables, including average number of faults per year and proportion of faults occurring in shallow water. If the fault occurs in shallow water — as is true in most cases† — the net length of cable added to the system and the resulting attenuation increase, are small. Several shallow-water faults might be permis-

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* The length of a cable is greater than the length of the route because of the need to pay out slack. The slack allowance, which averages 5 per cent in deep water on this route, helps to assure that the cable follows the contour of the bottom.

† Because of trawler activity, ship anchors and icebergs.

sible without adding a repair repeater. Therefore it was decided to let $n = 3$. Since the repair repeater is a 2-tube repeater while the regular repeater has 3 vacuum tubes, $n = 3$ corresponds to about 5 repair repeaters per cable.

To determine the maximum voltage E_m, it was necessary to consider blocking capacitors and earth potentials.

Based on laboratory life tests, the blocking capacitor developed has an estimated minimum life of 36 years at 2,000 volts. It is estimated that life varies inversely as about the fourth power of the voltage. The potential actually appearing on these capacitors is determined by the distance of the repeater from shore, the power potential applied to the system, and the magnitude and polarity of any earth potential.

Earth potential records on several Western Union submarine telegraph cables were examined. These covered a continuous period from 1938 to 1947, including the very severe magnetic storms of April, 1938, and March, 1940. It was judged reasonable to allow a margin of 400 volts (200 volts at each shore station) for magnetic storms during the final years of life of the system.

With an assumed maximum voltage of 2,300 volts on the end repeaters due to cable-current supply equipment, and 200 volts per end as allowance for the maximum opposing earth potential which the system would be permitted to offset without automatic reduction of the cable current, the voltage across the end repeater in late years of life (i.e., after line current had been increased to offset aging) would normally be 2,300 and would infrequently rise to 2,500. On the rare occasions where earth potential would rise above twice 200 volts, the cable current would be somewhat reduced and the transmission affected to a reasonably small extent. In the early years of life when the cable-current supply voltage would normally be about 2,000 volts, an opposing earth potential of twice 500 volts could be accommodated without affecting cable current; according to the telegraph cable records this would practically never occur. With conditions changing in this way over the years, the life of the blocking capacitors in the end repeaters was calculated to be satisfactory.

Accordingly E_m was established as 2,300 volts.

The system length L was estimated as about 1,985 nautical miles and the ultimate current I was estimated as 0.250 amperes, with a corresponding ultimate E_{rep} of about 62.8 volts.

Substituting in (3),

$$N = 55$$

$$N\text{-}n = 52 \text{ working repeaters}$$

$$S = 37.4 \text{ nautical miles.}$$

From a later estimate of $L = 1{,}955$ nautical miles, S calculates to be 36.9. The repeater design was based on this spacing in the deep sea temperature and pressure environment. Subsequently, after better knowledge had been obtained of the cable attenuation in deep water, the actual repeater spacing for the main part of the crossing was changed to about 37.4 nautical miles for the eastbound (No. 1) cable and 37.6 for the westbound. Only 51 repeaters were required in each cable.

Number of Channels

The number of channels which could be transmitted was determined by the upper and lower boundary frequencies. In this system, the bottom frequency was established at 20 kc, primarily because of the loss characteristics of the power separation filters.[3]

Preliminary studies were made to estimate the usable top frequency. For a system having a fixed number of repeaters, this frequency falls where the maximum permissible repeater gain equals the loss of a repeater section of the cable — which varies approximately as the square root of frequency. The repeater gain is the difference between the repeater input and output levels. The minimum permissible transmission level at the repeater input depends on the random noise (fluctuation noise) contributed by cable and repeaters, and on the specified requirement for random noise. The maximum permissible transmission level at the repeater output may depend on the modulation noise contributed by the repeaters below overload, or on overload from the peaks of the multi-channel signal complex. In this system, overload was found to be the controlling factor.

An important consideration was to provide enough feedback in the repeater so that at the end of 20 years the accumulated gain change (Mu-Beta effect) in all the repeaters would not cause the signal-to-noise performance to fall outside limits. The usable feedback voltage was scaled from the Havana-Key West design according to the relation that this voltage varies inversely as the $\frac{5}{3}$ power of the top frequency. Electron tube aging was estimated from laboratory life tests on Key West-Havana type tubes.

Concurrently, detailed theoretical and experimental studies were being conducted on the transmission design of a repeater suited to transatlantic use with the chosen type of cable, as discussed in a companion paper.[3] Intimate acquaintance with the repeater limitations led to a decision in 1953 to develop a system with a working spectrum of 144 kc (36 channels) and a top frequency of 164 kc. Use of compandors would not increase this top frequency appreciably.

Computed Noise

When the repeater design was established, the remaining theoretical work on signal-to-noise consisted in refining the determination of the repeater output and input levels; computations of system noise, and comparison of this with the objectives to establish the margin available for variations; and determination of the necessary measures in manufacturing and cable laying so that these margins would not be exceeded by the deviations from ideal conditions which would occur. These deviations assumed great importance, because they tended to accumulate over the entire length of the system, and because many of them were unknown in magnitude before the system was actually laid.

The repeater levels and the resultant system noise were computed as follows:

It was recognized that the output levels of different repeaters would differ somewhat at any given frequency. The maximum allowable output level of the highest-level repeater was computed by the criterion that the instantaneous voltage at its output grid would be expected to reach the load-limit voltage very infrequently. This is the system load criterion established by Holbrook and Dixon.[6] It premises that in the busy hour, the load-limit voltage (instantaneous peak value) should be reached 0.001 per cent of the time, or less. It is probable that the level could be raised 2 db higher than the one computed in this way without noticeable effect on intermodulation noise.

An important factor in the Holbrook-Dixon method is the talker volume distribution. Because of the special nature of this long circuit, a careful study was made of the expected United States talker volumes.

First, recent measurements of volumes on long-distance circuits were examined for the relation between talker volume and circuit length. They showed a small increase for the longer-distance circuits. This relation was extrapolated by a small amount to reach the 4000-mile value appropriate to the New York-London distance.

Second, an estimate was made of the probable trends in the Bell System plant in the next several years, which might affect the United States volumes on transatlantic cable calls.

The result of this was a "most probable U. S. volume distribution". This distribution, which had an average value of -12.5 vu at the zero level point, with a standard deviation of 5 db, agreed very well with one furnished by the Post Office and based on calls between London and the European continent. A further small allowance was then made for the contribution of signaling tones and system pilots which brought the resultant distribution to an average value of -12 vu at zero level of the system (the level of the outgoing New York or London or Montreal switchboard), and a standard deviation of 5 db. It is approximately a normal-law distribution (expressed in vu), except that the very infrequent high volumes are reduced by load limiting in the inland circuits.

The other data needed for system load computations are the number of channels, and the "circuit activity", i.e., the per cent of time during the busy hour that the circuit is actually carrying voice in a given direction (eastbound or westbound). The circuit activity value used in designing United States long-distance multi-channel circuits is 25 per cent; for the transatlantic system, 30 per cent was used.

The peak value of the computed system multi-channel signal is the same as the peak value of a sine wave having an average power of +17.4 dbm at the zero transmission level point of the system.

This value, together with the measured sine-wave load capacity of the undersea repeater, determines the maximum permissible output transmission level of the repeater. The measured sine-wave load capacity is about +13.5 dbm at 164 kc. Hence the maximum permissible output transmission level for the 164-kc channel is $+13.5 - 17.4 = -3.9$ db.

If the relative output levels of the various submarine repeaters were precisely known, the highest-level repeater could have an output transmission level of -3.9 db at 164 kc. An allowance of about 2 db was made for uncertainty in knowledge of repeater levels, giving -6 db as the design value for the maximum repeater output level at 164 kc.*

The repeater has frequency shaping in the circuit between the grid of its output tube and the cable. The maximum repeater output at lower frequencies is smaller than at 164 kc, but the maximum voltage on the output grid, from an overload standpoint, is approximately constant over the 20 to 164 kc band.

The transmission level of the maximum level repeater output is thus determined, based on load considerations. Another factor which might limit this level is modulation noise. This was found to be less of a restriction than the load limitation, however.

With the output level determined, the random noise and the modulation noise for the system can be computed. The random noise computation is made on the assumption that all repeaters are at the same level, and then a correction is made for the estimated differences in levels of the various repeaters. The equation is

$$N_0 = N_{in} + G - TL + 10 \log n + d_r$$

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* At the time of writing, the No. 1 cable (eastbound) is set up with a somewhat lower maximum output level than this; the safe increase in level will be determined later.

where N_0 = system random noise, in dba,* referred to zero transmission level

N_{in} = random noise per repeater in dba, referred to repeater input level

G = repeater gain in db

TL = transmission level of repeater output

n = number of undersea repeaters

d_r = db increase in noise due to differing output levels of the various repeaters as compared to the highest level repeater.

At the top frequency of 164 kc, $TL = -6$ db as seen above, $G = 60.7$ db, and N_{in} is about -55.5 dba, which corresponds to a noise figure of about 2 db. Hence for 52 repeaters,

$$N_0 = -55.5 + 60.7 - (-6) + 10 \log 52 + d_r = 28.4 + d_r$$

At lower frequencies, the noise power referred to repeater input is greater because part of the equalization loss is in the input circuit; the repeater gain is less, to match the lesser loss of a repeater section of cable; and the repeater output level is lower on account of the equalization loss from output grid to repeater output. This is shown in Table I.

TABLE I

Channel	N_{in} = Approx. Input Noise, dba	G = Approx. Repeater Gain, db	TL = Approx. Output Trans Level, db	N_0 = Resulting Noise dba
Top Freq.	-55.5	60.7	-6	$28.4 + d_r$
Middle	-53	45	-11	$20.2 + d_r$
Bottom Freq.	-46	22	-19	$12.2 + d_r$

In order to estimate d_r (which is a function of frequency) before the cable was laid, the factors were studied which might contribute to differences between the levels of the various repeaters. Estimates were made of probable total misalignment — by which is meant the level difference between highest-level and lowest-level repeaters. These values together with estimates of the resulting noise increases, are shown in Table II. This is based on the assumption that the repeater levels would be distributed approximately uniformly between highest and lowest. The position of a repeater along the cable route is not significant.

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* "dba" is a term used for describing the interfering effect of noise on a speech channel. Readings of the 2B noise meter with F1A weighting may be converted to dba by adding 7 db. dba may be translated to dbm (unweighted) by noting that flat noise having a power of 1 milliwatt over a 3,000-cycle band equals approximately +82 dba, and that 1 milliwatt of 1,000-cycle single-frequency power equals +85 dba.

TABLE II

Channel	M = Estimated Misalignment	d_r = Resulting Noise Increase	N_0 = Resulting System Random Noise (Approx.)
Top	12 db	7.4 db	36 dba
Middle	10 db	6.0 db	26 dba
Bottom	6 db	3.4 db	16 dba

A study was made of the expected intermodulation noise. This noise is affected by repeater level differences, by talker volumes, and by circuit activity. It has a time distribution, the most attention being given to the root-mean-square modulation noise in the busy hour.

Modulation noise was computed in two ways: by the Bennett method,[7] and by the Brockbank-Wass method.[8] Results by the two methods are in fairly good agreement. The values computed by the Bennett method are shown in Table III.

Because noise powers, not dba, are additive, these values of modulation noise would contribute only a very small amount to the total noise in the deep-sea cable system, as previously stated.*

Other possible contributory sources of noise in the deep-sea cable system are noise in the terminals, noise picked up in the shore lead-in cables, and corona noise in the repeaters. The system has been designed so that the expected total of these is small. Hence the estimate of total deep-sea cable system noise, made before cable-laying, gave the values shown in Table IV, to the nearest db.

Misalignment Control

Objective

Since the noise objective for the deep sea cable link was set as 36 dba in the joint meetings of the British Post Office and Bell System Representatives[1], the above estimate of system noise led in turn to the objective that the system be manufactured and laid in such a way that the misalignment, including effects of seasonal temperature change, should be no greater in the top channel than the value assumed in the estimate, which was 12 db. Half of this was alloted to initial misalignment and half to effects of temperature change. Greater misalignments were permissible at lower frequencies.

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* The following table for adding two noises expressed in dba shows the magnitudes of the increases:

db difference between larger and smaller noises	2	4	6	8	10	15	20
Resulting db to be added to larger noise to get sum of the two	2.1	1.4	1.0	0.6	0.4	0.1	0+

TABLE III

Channel	Weighted Noise in dba at Zero Transmission Level		
	Second Order Products	Third Order Products	Total
Top	8.2	8.5	11.3
Middle	0.2	3.8	5.4
Bottom	−1.8	2.5	3.9

TABLE IV

Channel	Estimated System RMS Noise at 0 db Transmission Level	
	dba	dbm (Psophometer†)
Top	36	−48
Middle	26	−58
Bottom	16	−68

† The psophometer is the C.C.I.F. circuit noise meter. On message telephone circuits, dbm (psophometer) + 84 = dba using C.C.I.F. 1951 weighting and Bell System F1A weighting.

Control of this misalignment required extensive consideration in the equalization design of the system.

Causes of Misalignment

The basic causes of misalignment can be grouped as follows: those producing unequal repeater levels when the system is first laid; those resulting from changes in cable loss produced by changes in sea-bottom temperature; and those from aging of the cable or repeaters.

There are a large number of possible causes of initial misalignment. While the cable and repeaters were manufactured within very close tolerances to their design objectives, they could not exactly meet those objectives. In addition, the cable loss as determined in the factory must be translated to the estimated loss on sea-bottom, and the length of each repeater section must be tailored in the factory so that its expected sea-bottom loss will best match the repeater gain. Possible sources of error in this process include: uncertainty in temperature of the cable when it is measured in the factory, and in its temperature on the sea-bottom; uncertainty in temperature and pressure coefficients of attenuation; changes in cable loss between factory and sea-bottom conditions, not accounted for by pressure and temperature coefficients.

These latter changes in cable loss were called "laying effect". The determination of the magnitude of laying effect, and its causes, are discussed in the paper on cable design.[2] Suffice it to say here that after measuring the loss of a length of cable in the factory and computing the sea-bottom loss, the computed result was a little greater than the actual sea-bottom loss. The difference, i.e., the laying effect, was approximately proportional to frequency, and was greater for deep-sea than for shallow-water conditions. Its existence was confirmed by precise measurements on trial lengths of cable, made early in 1955 in connection with cable-laying tests near Gibraltar.

Laying effect had been suspected from statistical analysis of less precise tests of repeater sections of cable generally similar to transatlantic cable, as measured in the factory and as laid in the vicinity of the Bahamas. However, the repeater design had of necessity been established before the Gibraltar test results were known. The consequence was a small systematic excess of repeater gain over computed cable loss, approximately proportional to frequency, and amounting at the top frequency to about 0.04 db per nautical mile on the average, for deep-sea conditions, and about 0.025 db per mile for shallow-water conditions. While this difference appears small, it would accumulate in a transatlantic crossing of some 1,600 miles of deep sea and 350 miles of relatively shallow sea, to about 75 db at the top frequency. This would be enough to render almost half of the channels useless if no remedial action were taken.

After the system is laid, changes in cable loss or repeater gain may occur. These may be caused by temperature effects and by aging of cable or repeaters.

Comprehensive studies* of the expected amounts of temperature change were made both before and after the 1955 laying. These gave an estimate of 0 to ±1 degree F annual variation in sea-bottom temperature in the deep-sea part of the route (about 1,600 nautical miles) and perhaps ±5° F on the Continental shelves (about 330 nautical miles). Use of these figures leads to a ±5-db variation in system net loss at 164 kc from annual temperature changes. If the deep-sea bottom temperature did not change at all, the estimated net loss variation due to temperature would be about half of this.

Control of Misalignment

The first line of defense against variations leading to misalignment was the design and production of complementary repeaters and cable. This is discussed in companion papers.

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* Factual data on deep sea bottom temperatures are elusive. Many of the existing data were acquired by unknown methods under unspecified circumstances, using apparatus of unstated accuracies. Statistical analysis of selected portions of the data leads to the quoted estimates.

Signal-to-noise changes from undersea temperature variations were minimized by providing adjustable temperature equalizers at both the transmitting and the receiving terminals, and devising a suitable method of choosing when and how to adjust them.

Partial compensation for laying effect was carried out at the cable factory by slightly lengthening the individual repeater sections. In the 1955 cable, where the factory compensation was based on early data, the increased loss compensated for about two-fifths of the laying effect at the top frequency. In the 1956 cable, which had the benefit of the 1955 transatlantic experience, the compensation was increased to nearly twice this amount. Since the loss of the added cable is approximately proportional to the square root of frequency and the laying effect is approximately directly proportional to frequency, the proportion of laying effect compensated varied with frequency, and a residual remained which had a loss deficiency rising sharply in the upper part of the transmitted band.

The remainder of the laying effect, which was not compensated for in the factory, as well as other initial variations, were largely compensated by measures taken during cable laying at intervals of 150 to 200 miles. The whole length of the cable was divided into eleven "ocean blocks", each either four or five repeater sections long. At each junction between successive ocean blocks, means were provided to compensate approximately for the excess gain or loss which had accumulated up to that point.

These means were twofold. The first means was adjustment of the length of the repeater section containing the junction. For this purpose, the beginning of each block, except the first, was manufactured with a small excess length of cable. This was to be cut to the desired length as determined by shipboard transmission measurements.

The second means was a set of undersea equalizers. These equalizers were fixed series networks, encased in housings similar to the repeater housings but shorter.

Before the nature of the laying effect was known, it had been planned to have equalizers with perhaps several shapes of loss versus frequency; but to combat laying effect, nearly all were finally made with a loss curve sloping sharply upward at the higher frequencies, as shown in Fig. 3.* Because the equalizer components had to be manufactured many months in advance and then sealed into the housings, last minute designs of undersea equalizers were not practical. The proven-integrity principle prevented use of adjustable units. Because the equalizers were series-

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* This characteristic was based on a statistical analysis of the data on some similar cable laid for the Air Force project.

type, each block junction was located at approximately mid-repeater section to minimize the effects of reflections between equalizer and cable impedances.

The actual adjustments at block junctions were determined by a series of transmission measurements during laying, as described in the companion paper on cable laying.[9] Six equalizers were used at block junctions in the 1955 (No. 1) cable, and eight in the 1956 (No. 2) cable.

The result of all the precautions taken to control initial misalignment was, in the 1955 cable, to hold the initial level difference between highest and lowest-level repeaters to about 6 db near the top frequency and to values between 4 and 9 db at lower frequencies, the 9 db value occurring in the range 50 to 70 kc where there is noise margin. In the 1956 cable, the level difference was about 4 db at the top frequency, and from 2 to 7 db elsewhere in the band.

Shore Equalization

The equalization to be provided at the transmitting and receiving ends of the North Atlantic link had these primary functions:

1. For signal to noise reasons, to provide a signal level approximately flat with frequency on the grid of the third tube of the undersea repeaters.
2. To equalize the system so that the received signal level is approximately constant over the transmitted band.
3. To keep the system net loss flat, regardless of temperature variations in the ocean. (A change of 1° F in sea-bottom temperature would cause the cable loss to change by 2.8 db at 160 kc and less than this at lower frequencies. The amplifiers are relatively unaffected by small temperature changes.)
4. To provide overload protection for the highest level repeater.
5. To incorporate some adjustment against possible cable aging.

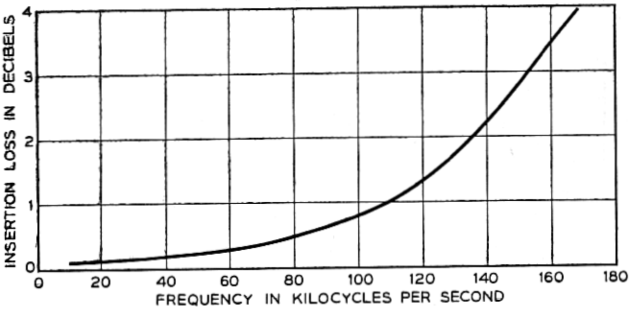

Fig. 3 — Undersea equalizer — loss-frequency characteristic.

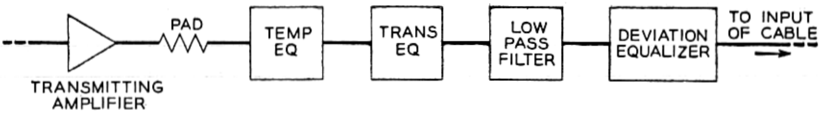

Fig. 4 — Transmitting equalizers — block schematic.

A portion of the transmitting terminal is shown in block schematic form in Fig. 4. All of the equalizers are constant resistance, 135 ohm unbalanced bridged-T structures. Their functions are as follows:

Transmitting Temperature Equalizer — It was estimated that the cable loss change from temperature variations would not exceed ±5 db at the top of the transmitted band. The change in cable loss versus frequency due to temperature variations is approximately the same as if the cable were made slightly longer or shorter, and so the temperature equalizer was designed to match cable shape. Temperature equalizers are used both in the transmitting and receiving terminals to minimize the signal-to-noise degradation caused by temperature misalignment. Each equalizer provides a range of about ±5 db at the top of the band, the loss being adjustable in steps of 0.5 db by means of keys. See Fig. 5.

This range might appear to be more than necessary, but it must be borne in mind that the sea bottom temperature data left much to be desired in precise knowledge of both average and range.

Transmitting Equalizer — The transmitting equalizer was so designed that with the temperature equalizer set at mid-range and with repeaters that match the cable loss, the signal level on the grid of the output tube of the first repeater would be flat with frequency. The loss-frequency characteristic is shown on Fig. 6.

L.P. Filter — This filter transmits signals up to 164 kc and suppresses by 25 db or more, signals in the frequency range from 165 to 175 kc. Its purpose is to prevent an accidentally applied test tone from overloading the deep sea repeaters should such a tone coincide with the resonance

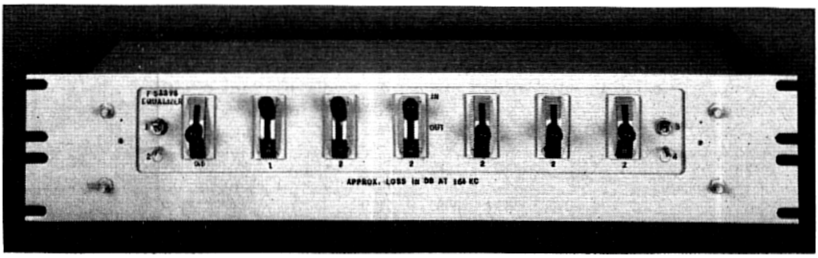

Fig. 5 — Transmitting temperature equalizer.

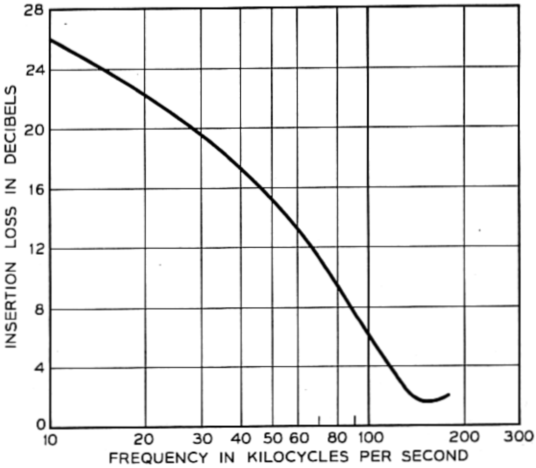

Fig. 6 — Transmitting equalizer — loss-frequency characteristic.

of the crystal used in a repeater for performance checking. The gain of a repeater to a signal applied at the resonance frequency of its crystal is about 25 db greater than at 164 kc.

Deviation Equalizer — The transmitting deviation equalizer is used to protect the highest level repeater from overload. The design is based on data obtained during the laying indicating which repeater was at the highest level at the various frequencies. The characteristic of this equalizer is shown on Fig. 7.

A portion of the receiving terminal is shown in block schematic form on Fig. 8. The generalized function of the equalizers is to make the signal level flat versus frequency at the input to the receiving amplifier No. 2. The specific functions of the various equalizers are as follows:

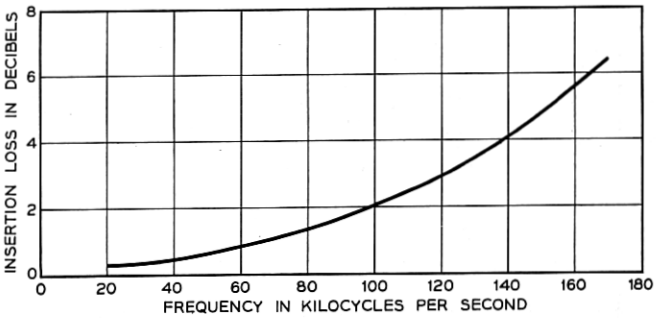

Fig. 7 — Transmitting deviation equalizer — loss-frequency characteristic.

Cable Length Equalizer — In planning the system, an estimate was made of how far the last repeater (receiving end) would be from the shore. Considerations of interference and level dictated a maximum distance not exceeding approximately 32 miles. For protection against wave action, trawlers and similar hazards, the repeater should be no closer than about five miles. To take care of this variation, a cable length equalizer was designed that is capable of simulating the loss of 10 miles of cable, adjustable in 0.5 db steps at the top of the frequency band. Two of these could be used if needed. Once the system is laid, this equalizer should require no further adjustment unless it is used to take care of cable aging or a cable repair near shore.

Receiving Fixed Equalizer — This is the mop-up equalizer for the system. A final receiving equalizer, Fig. 9, has been constructed for the first crossing. Another, tailored to the No. 2 cable, will be designed on the basis of data taken after completion.

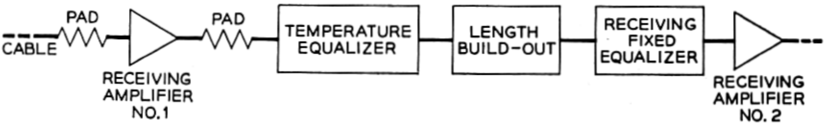

Fig. 8 — Receiving equalizers — block schematic.

Receiving Temperature Equalizer — The receiving temperature equalizer is identical with the transmitting temperature unit.

OPERATIONAL DESIGN

General

The operational design of a transmission system considers the supplementary facilities which are needed for operation of the main transmission facility, for its supervision and for its maintenance. In the present instance, these facilities include the cable station power plants for driving the carrier terminals and high frequency line, the carrier terminals themselves and their associated carrier supply bays, the telephone and telegraph (speaker and printer) equipments needed for maintenance, supervision and administration of the overall facility, the pilots, protection devices and alarms and the maintenance and fault locating equipment.

Power Supplies

With the exception of the plants for cable current supply, the power plants at Clarenville and Oban are relatively conventional, and follow telephone office techniques which are standard for the telephone administration of the particular side of the Atlantic on which they are located. They will not be discussed here, although it might be well to point out that the equipment supply for the Bell equipment is direct current, obtained from floated storage batteries, while the supply for the Post Office equipment is alternating current from rotary machines driven normally from the station ac supply, with storage battery back-up.

The cable current supplies for the North Atlantic link[10] are complex and highly special. It is pertinent to discuss here briefly the requierments which beget this complexity. To assist in this, an elementary schematic of the cable power loop is shown in Fig. 10.

The following main requirements governed the design of these plants:

1. Constant maintenance of uniform and known current in the power loop.
2. Protection of HF line against faults induced by failures in power bays.
3. Protection of HF line against damage from power voltage surges caused by faults in the line itself.

Maintenance of constant and known operating current in the line is very important from the standpoint of system life because of the dependence of the rate of electron tube aging on the power dissipated in the heaters.[11]

The principal factor which tends to cause variations in the line current is the earth potential which may appear between the terminals of the system. This potential may be of varying magnitude and of either po-

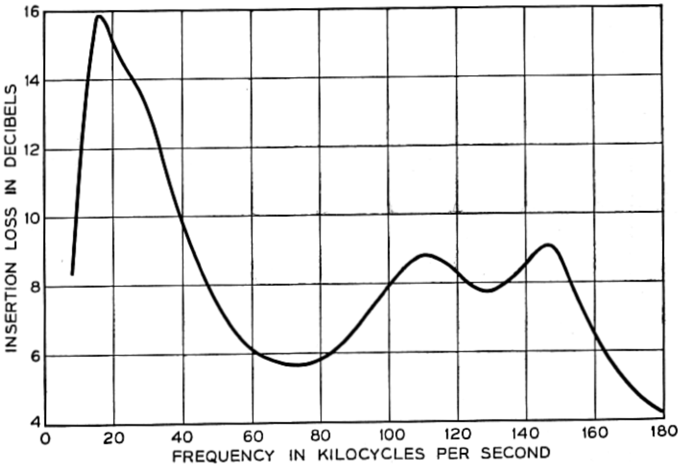

Fig. 9 — Receiving fixed equalizer — loss-frequency characteristic.

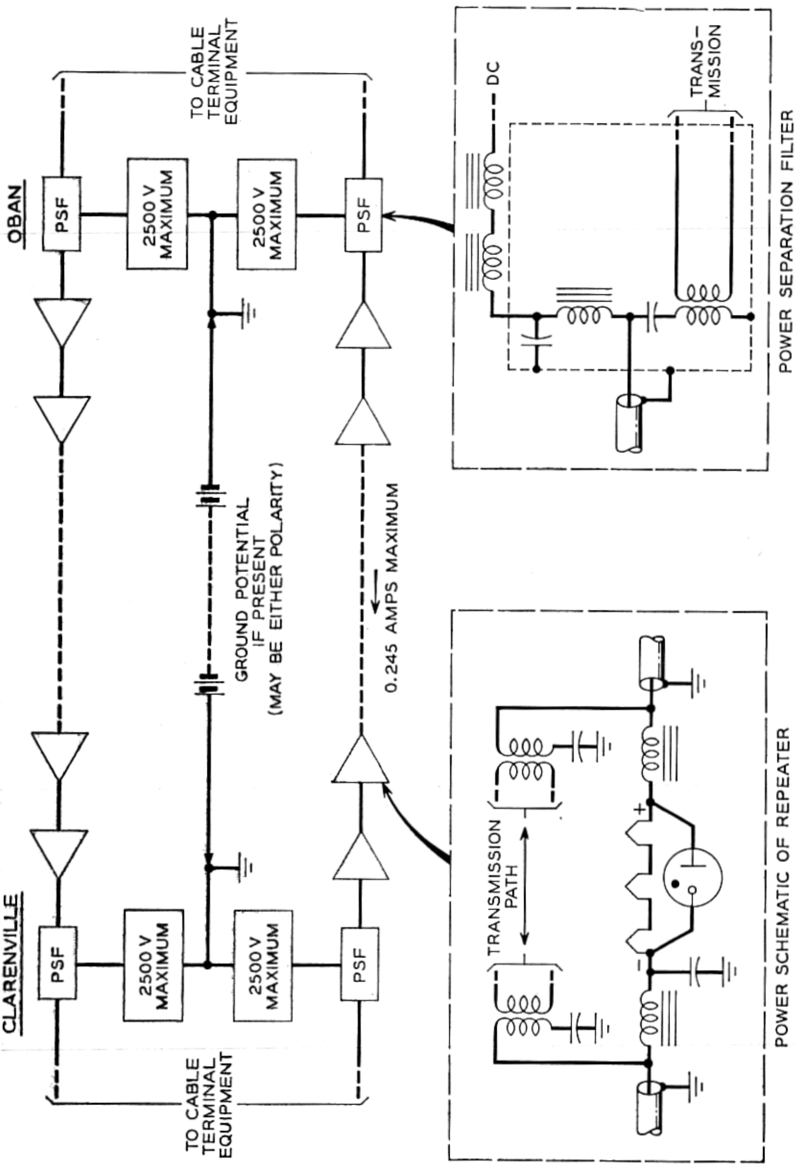

Fig. 10 — Cable power loop — elementary schematic.

larity. Consequently, it may either aid or oppose the driving potential applied to a particular cable. The power circuit regulation is such that the presence of an aiding potential will be completely compensated, while opposing potentials will be compensated only to the degree possible with the maximum of 2,500 volts applied by the terminal plants. Beyond this point, the line current will be allowed to drop, so as to avoid excessive potential across the power filter capacitors in the shore end repeaters.

Line faults caused by failures or misoperation of the power supplies must be carefully guarded against. Such failures might result in surges on the line, or excessive voltage or current. Protection against surges takes the form of retardation coils in the terminal power separation filters, which limit the rate of current change to tolerable values.

Failure of the capacitors in these filters could also create dangerous surges. The protection here takes the form of a large voltage design margin.

Faults in the HF line of importance from the power feed standpoint are short circuits to ground, and opens. The former tend to result in excessive currents, the latter, excessive voltages. Very fast acting protection in the terminal power bays is required to cope with these, and series electron tube regulators provide the means.

Terminal Plan

The plan of design of transmission terminal equipment, shown in Fig. 2, was based on the following objectives:

(a) Use of standard, or modified standard equipment as far as possible.

(b) To facilitate supply and maintenance of standard equipment, use of Bell System equipment in North America and Post Office equipment in the United Kingdom.

(c) Provision of full duplicate equipment and means for quick shift between regular and alternate.

(d) Provision of special equipment to fit Canadian requirements.

(e) Provision for ample order-wire (speaker and printer) equipment, partly because there is no alternate undersea route.

(f) Provision of no automatic loss regulation, because the loss changes are so slow; provision of three link pilot frequencies as a basis for manual regulation.

Much of the equipment is standard. This includes group modems, group connectors, pilot supply, frequency-shift telegraph equipment for printer circuits, etc. Supergroup modulators are modified standard coaxial carrier equipment. The channel modems for speaker and printer circuits are a combination of Type-C open-wire carrier active equipment,

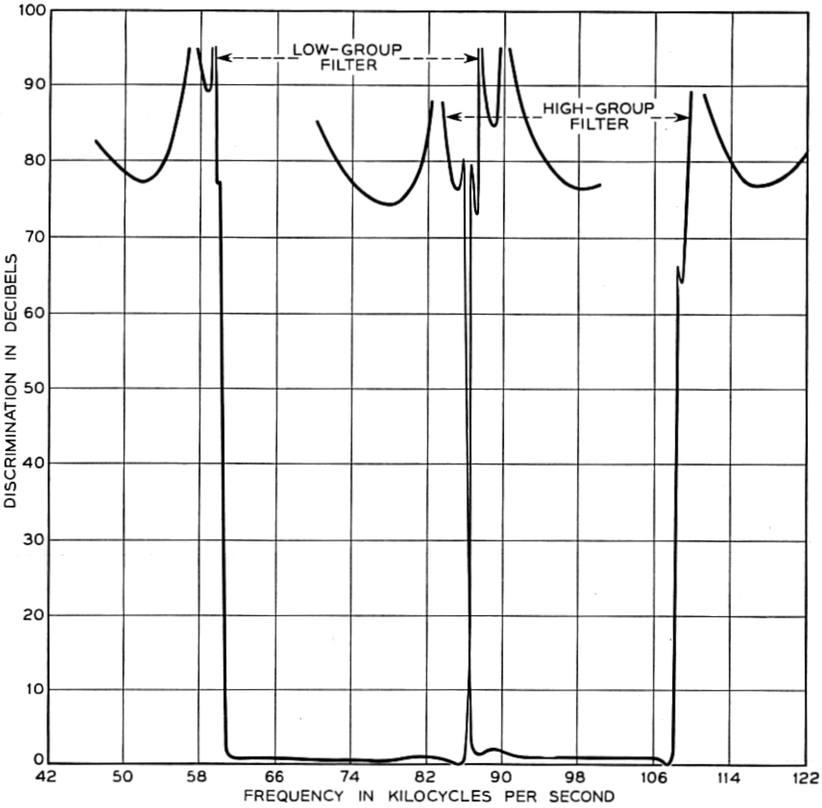

Fig. 11 — Splitting filters — loss frequency characteristic.

and filters designed for a military carrier system. The transmitting output amplifier is a modified version of one used in the Havana-Key West submarine cable system terminals; the modifications include broader frequency band, lower modulation and sharper overload cutoff. As in the coaxial carrier system, hybrid coils are provided at points in the Bell equipment where quick patching is needed.

The agreed Canadian bandwidth quota is 26 kc,[1] corresponding to six and one-half message telephone channels. The split between the 6½ Canadian channels and the remaining 5½ U.S. channels in the "split group" was accomplished by specially-designed group-frequency splitting filters, with very sharp cutoff. The loss-versus-frequency characteristics of these filters are shown in Fig. 11. The resulting Canadian half telephone channel next to the cut-apart was broad enough to accommodate twelve frequency-shift telegraph channels with 120-cycle carrier telegraph spacing. It is planned to use one of these for automatic regulation of the other eleven. The U.S. half channel is at present unassigned.

Two telephone order wires (speakers) and two teletype order wires (printers) are provided for maintenance and administration purposes.

The two speakers occupy a 4-kc telephone channel which is the lower sideband of 20 kc on the line. The 4-kc band is divided into halves by Bell Type-EB split-channel equipment, which yields two narrow-band telephone channels. One of these is reserved for a "local" Clarenville-Oban circuit, available at all times to the personnel at these terminals. It constitutes a cleared channel which could be of great benefit in emergencies which might arise. The other narrow-band telephone channel, the "omnibus speaker", is extended through to other control points including the system metropolitan terminals.

The two printer circuits are frequency-shift voice-frequency telegraph channels, occupying line frequencies just below 16 kc. These are both brought to dc at Clarenville and Oban, and extended by carrier telegraph to the metropolitan terminals. One is normally a "through" circuit with teletypewriters at the metropolitan terminals only, and the other is an "omnibus" circuit with teletypewriters connected at Oban, Clarenville and other control points, permitting message interchange between all connected points.

92-kc group frequency pilots are transmitted over the Clarenville-Oban link only, and blocked at its ends. The line frequencies corresponding to the 92-kc group frequencies are 52, 100 and 148 kc. These pilots are used for manual regulation and maintenance of the Clarenville-Oban link. Information derived from them governs the manual setting of the temperature equalizers. The sending power of the 92-kc pilots is regulated to within ±0.1 db variation with time.

84.080-kc group frequency pilots also appear on this link. These, however, are system pilots applied at the metropolitan terminals. They are useful for evaluation of overall system performance and for quickly locating transmission troubles.

Alarms are provided in the manner usual for multi-channel telephone systems. A special feature of the pilot alarm system is the "alarm relay channel", a third voice-frequency carrier telegraph channel just below the printer channels in line frequency. If all three eastbound 92-kc pilots fail to reach Oban, a signal is transmitted over the westbound cable which brings in a major alarm at Clarenville, and vice versa. This major alarm would provide news of a cable failure immediately to the transmitting cable terminal station. Failure of the pilot supply would, of course, give the same alarm. The alarm relay channel circuit is arranged so that if it fails it does not give the major alarm.

A special alarm system for the cable current supply is described in the companion paper on that equipment.[10]

Fault Location

Length and inaccessibility have always imposed difficult requirements on fault locating techniques for undersea cable systems. Before the advent of repeatered systems, much effort was expended on use of impedance methods — i.e., those involving resistance and electrostatic capacitance measurements to locate a fault to ground, or a break.* Some work has been done also on magnetic pickup devices towed along the route by a ship.

With the advent of undersea repeaters, the problem has become even more difficult, both because of the effect of the repeater elements on impedance measurements, and because a fault may interrupt transmission without affecting the dc loop.

It has been necessary, therefore, to reassess the whole problem of fault location.

Location of Faults Affecting the DC Power Loop

Three types of measurement are made on submarine cables at present:

(a) Center conductor resistance, assuming a short circuit or a sea water exposure at some point, which might be either a fault or a break.

(b) Dielectric resistance, assuming a pinhole leak through the dielectric and a sea water exposure.

(c) Electrostatic capacitance, assuming a center conductor break insulated from sea water.

By these methods, faults and breaks in non-repeatered cables can be located although the accuracy of determination, and indeed the practical success of the operation, is dependent on the nature of the fault, the situation with respect to earth potential, the skill of the craftsman and many other factors.

The presence of cold repeaters in the circuit adds considerably to the difficulty, both because of the resistance/temperature characteristic of the electron tube heaters (153 in series with each cable) and because of polarization effects exhibited by the castor oil capacitors in the trans-

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* In the literature, "fault location" is a generalized term encompassing the field. A "fault" is an exposure of the cable conductor to the sea without a break in the conductor. A "break" is an interruption of the conductor with or without exposure to the sea.

atlantic repeaters. These capacitors have a storage characteristic which varies with the magnitude of applied voltage, duration of its application and the temperature.

Because of this, the usual methods of fault location are expected to give results of doubtful accuracy and so a new approach is being made to the problem. The results of the work to date are beyond the scope of this paper.

Location of Transmission Faults

The previous section deals with the situation where the dc power loop has been opened or disturbed. Of equal importance is the location of transmission faults when the power loop is intact.

For this purpose, use is made of the discrete frequency crystal provided in each repeater.[3] This crystal is effectively in parallel with the feedback circuit of the amplifier, and at its resonant frequency the amplifier has a noise peak of the order of 25 db, with an effective noise band of about 4 cycles. When one repeater fails, it is possible to recognize the noise peak of each amplifier from the receiving end back to the failed unit. The noise peaks from the faulty unit and all preceding amplifiers will be missing, indicating location of the trouble. Noisy amplifiers can be singled out by an extension of the technique.

Testing and Maintenance

Routine testing and maintenance activities at Oban and Clarenville can be divided into four parts: for the carrier terminals, for the station power equipment, for the cable current power units and for the high frequency line. Usual methods apply and the usual types of existing test equipment were provided with one exception.

The exception is a newly designed transmission measuring system. The system employs a decade type sending oscillator with continuous tuning over the final 1-kc range. Provision is built-in for precise calibration of output level. The receiving console contains a selective detector functioning as a terminating meter of 75-ohm input impedance, and can measure over the range − 120 to 0 dbm. Coils are supplied to permit measuring over 135-ohm circuits. The detector can be calibrated for direct reading when used as a terminating meter.

The system covers a frequency range of 10 kc to 1.1 mc. It is useful, therefore, for measuring much of the standard British and U.S. designed carrier terminal equipment as well as for normal line transmission measurements over both the North Atlantic and Cabot Strait (Newfoundland-Nova Scotia) submarine lines.

A special transmission measuring set is provided in the receiving console which facilitates measurements in the crystal frequency region 166–175 kc. This set is used for evaluating the performance of individual repeaters from shore. As an oscillator, it is capable of delivering an output of up to +8 dbm into a 75-ohm load, with exceptional frequency stability and finely-adjustable, motor-driven tuning. This is useful in locating and measuring the narrow-band response peaks of individual repeater crystals. The oscillator frequency is varied in the region of a particular peak, and the received power is measured at the peak frequency and at nearby frequencies. At the peak frequency, the crystal removes nearly all feedback in the repeater. Changes in repeater internal gain can thus be determined from shore.

As a detector, the set can measure from −110 to −60 dbm in a bandwidth of about 2 cycles. This enables it to measure crystal noise peaks which may be spaced as closely as 50 cycles apart. To reduce the random variations in such narrow-band noise, a "slow integrate" circuit, of the order of 10 seconds, is provided. Thus the crystal noise peaks can be compared in magnitude with the system noise level at closely adjacent frequencies.

ASSEMBLY AND TEST OF SYSTEM

General

Assembly and initial testing of the North Atlantic link occupied a span of about three years. Because of the geographical and political factors involved the job was a difficult one and required close cooperation among individuals in many different organizations on both sides of the ocean.

Clarenville

The cable station at Clarenville houses the carrier terminal, cable terminating and power equipment at the junction of the North Atlantic and Cabot Strait links. It was designed by United States architects from requirements furnished by A. T. & T. engineers and was approved by the other parties to the enterprise. The building was constructed by a Canadian firm under the supervision of a Canadian architect. The equipment was put in place and connected by installers of the Northern Electric Company and tested by representatives of Bell Telephone Laboratories, Eastern Telephone and Telegraph Company, Northern Electric Company and the British Post Office.

As Newfoundland is an island, shipments of equipment and supplies to Clarenville were carried by sea or air to St. John's where they were trans-shipped by rail to Clarenville.

Oban

The cable station at Oban was executed by British contractors from designs drawn up by the British Post Office. Its equipment was installed by a British electrical contracting firm. Two Western Electric Company installers were present at Oban during the installation of the American-made cable terminating equipment and cable current supply bays to provide necessary liaison and interpretation of drawing requirements. The Oban equipment was tested by representatives of the British Post Office, Bell Telephone Laboratories and the firm that did the installing.

Here too, it was necessary to ship by boat or air, with subsequent trans-shipment by train and by truck.

Undersea Link

Perhaps the most interesting phase of all was the handling of the undersea section. The actual laying is described elsewhere, but much effort was required before the cable ship ever left the dolphins at the cable manufacturing plants.

Most of the cable was manufactured at the plant of Submarine Cables, Ltd., at Erith, on the Thames about fifteen miles downstream from London. A smaller quantity of cable was manufactured by Simplex Wire and Cable Corporation at its plant in Newington, N.H. As the cable was completed it was coiled in repeater section lengths in huge tanks. The ends of each repeater section were left available at a "splicing platform" where the repeaters, manufactured at Hillside, N.J., were spliced in. Spliced repeaters were located in water filled troughs for protection against overheating while testing.

All repeaters were armored by Simplex at Newington. This involved their transportation by truck from the Western Electric shop at Hillside where the flexible repeaters were manufactured, to Newington. While this sounds simple it was actually a very carefully planned and controlled operation because of the need to avoid subjecting the units to any but the most necessary and unavoidable hazards. Consequently, the truck used for the purpose was specifically selected for size and construction and was provided with a heating unit in the body. The route was carefully surveyed in advance for unusual hazards and the truck speed was limited to a very modest value.

After the repeaters were armored, those to be incorporated in Simplex-made cable were spliced at Newington. Those destined for application in

British-made cable were shipped by truck, following the same precautions, to Idlewild Airport in New York. From there they proceeded by special freight plane — one or two at a time — to London Airport. Here they were again trans-shipped by truck to Erith.

The repeaters were housed in shipping cases[12] of a very strange shape and considerable size. These cases were provided with max-min thermometers and with impactograph devices that would record the maximum acceleration to which the repeaters had been subjected.

When ship loading time arrived, the cable and its contained repeaters were transported over a system of sheaves from the tanks of the cable manufacturer to the tanks on shipboard. This process offered no particular obstacle so far as the cable itself was concerned, but the requirement against unnecessary bending of the repeater meant that a great deal of special attention had to be given to avoiding unnecessary deviations from a straight run, and to lifting the repeaters around sheaves where the direction of the loading line changed materially. Auxiliary protection was provided on each repeater in the form of angle irons with flexible extensions on each end which served to restrict any bending to the core tube region of the repeater and safely limited the magnitude of the bends in this region.[3] One further precaution was observed — that of energizing the repeaters during the loading process. This accomplished two things. First, it permitted continuous testing; second, it reduced the hazards of possible damage to the electron tubes during loading, as the tungsten heaters are much more ductile when hot and the glassware of the tube is more resistant to shock and vibration.

SYSTEM PERFORMANCE

General

At the time of this writing, the No. 2 cable has just been laid, but the No. 1 cable has had eleven months of successful life under test, a pre-service period of probably greater duration than has been granted to any land system of comparable length and cost. It has been under constant observation and test, largely by the people who will operate it when it goes into service. The pre-service measurements have been much more extensive, in quantity and scope, than the routine tests which will be made after the system goes into service.

Net Loss Tests

Net Loss versus Frequency

Results of measurements in June, 1956, on the No. 1 cable are shown in Figs. 12 and 13. The former covers the equalized high-frequency line.

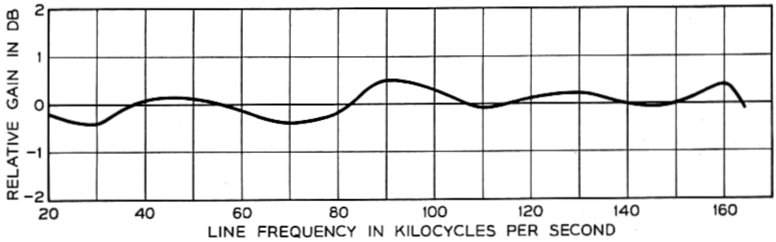

Fig. 12 — Gain versus line frequency — No. 1 cable.

Fig. 13 gives the corresponding group-to-group frequency response of the deep-sea link. These frequency characteristics will vary a little from time to time, depending partly on the change since the last adjustment of the temperature equalizer.

Note that while the slope in gross cable loss between 20 and 164 kc is about 2,100 db, the net loss of the equalized high frequency line over this band varies only about 1 db.

Net Loss versus Time

The net loss of the undersea system (cable plus repeaters) has decreased slowly since the system was laid. The decrease is approximately cable shape, proportional to the square root of frequency. In a year it has amounted to about 5 db at the top frequency. In the early months the change was almost directly proportional to time, but later the rate slowed, as shown in Fig. 14.

The changes shown in the figure are due partly to change in cable temperature and partly to slow aging of the cable. Detailed studies of repeater crystal frequency changes have resulted in only an approximate separation into temperature effects and aging. However, it seems reasonable to assume that at the end of a one-year cycle there would be little

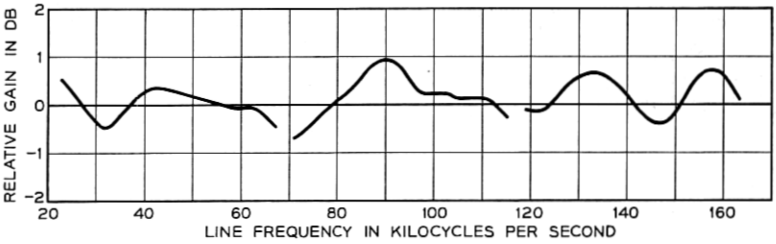

Fig. 13 — Group to group frequency response — No. 1 cable.

if any net change in the cable temperature averaged over the whole cable length. The greatest possibility of change would be in the shallow-water sections, and crystal measurements indicate that at the end of a year the average temperature of the shallow-water sections returned nearly to its initial value. Hence about 5 db seems chargeable to one year's aging. Extrapolation into the future, however, is uncertain. Theoretical considerations lead to the idea that the rate of cable aging should decrease.

Information on long-term change in transmission loss of previous cables is very limited. The Havana-Key West cables were accurately measured just after laying, and again five years later. The change in that system due to aging is very small, if indeed there is a change. That cable is generally like the transatlantic, though it is smaller and has a perhaps significant difference in construction of the central conductor.

The above applies to the net loss of the undersea part of the system only. The group-to-group net loss variation with time of the Clarenville-Oban link has been held within a much smaller range by temperature equalizer adjustments. Practices have been worked out which it is believed will hold the in-service variation with time to a fraction of a db.

Net Loss versus Carrier Frequency Power Level

Single-frequency tests of carrier frequency output power versus input power were made, up to a test power a little below the estimated overload of the highest-level repeater. An increase of 0.1 db in system net loss occurs at a power 2 to 3 db below the load limit of the transmitting amplifier. This is about 15 or 16 db above the expected rms value of the in-service system busy hour load. The 0.1 db change is presumably due to the cumulative effect of smaller changes in several of the undersea amplifiers.

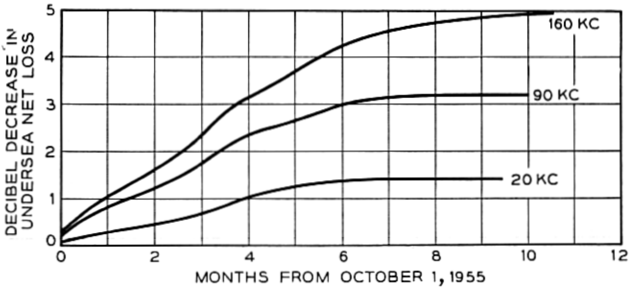

Fig. 14 — Change in system gain in first eleven months.

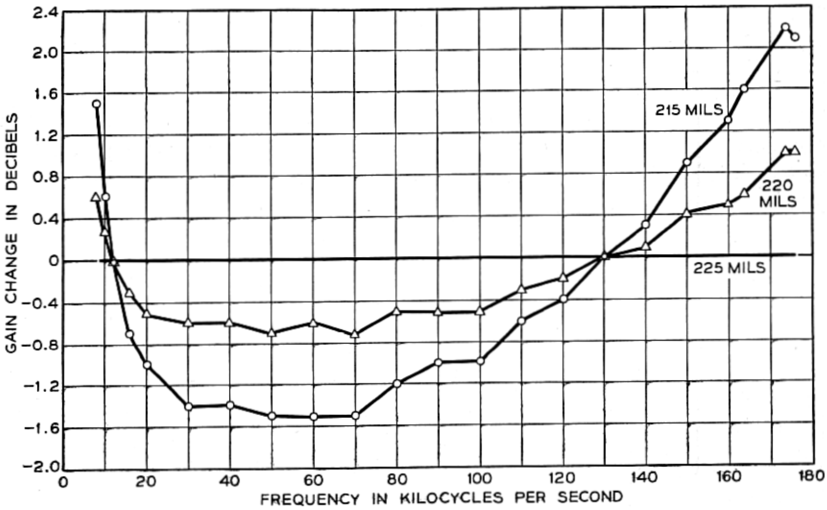

Fig. 15 — Effect of cable current on system gain — No. 1 cable.

Net Loss versus DC Cable Current

Changes in cable current affect the repeater gain to a slight extent, the amount depending on the magnitude and phase of the feedback in the repeater as a function of frequency. Measured changes in the loss of the 2,000-mile system, for currents of 5 and 10 milliamperes less than the normal value of 225 milliamperes, are shown in Fig. 15. Under normal conditions the automatic control will hold the cable current variation within ±0.5 milliampere.

The shape of the curve on Fig. 15 is almost the same as that computed in advance from laboratory measurements on model repeaters.

System Noise

Shown in Fig. 16 are values of noise on the No. 1 cable system measured in the Fall of 1955 and again in the Spring of 1956. The noise increase is compatible with the decrease in undersea system net loss during this period. To prevent overload, the loss in the transmitting temperature equalizer has to be increased as the undersea loss decreases; this lowers the levels of the various parts of the undersea system by various amounts.

The noise shown in the top channel exceeds the 36 dba objective by a small amount. The excess can be recovered, if necessary, by certain changes in the terminals without recourse to compandors.

Fig. 16 shows also the noise on the No. 2 cable system shortly after

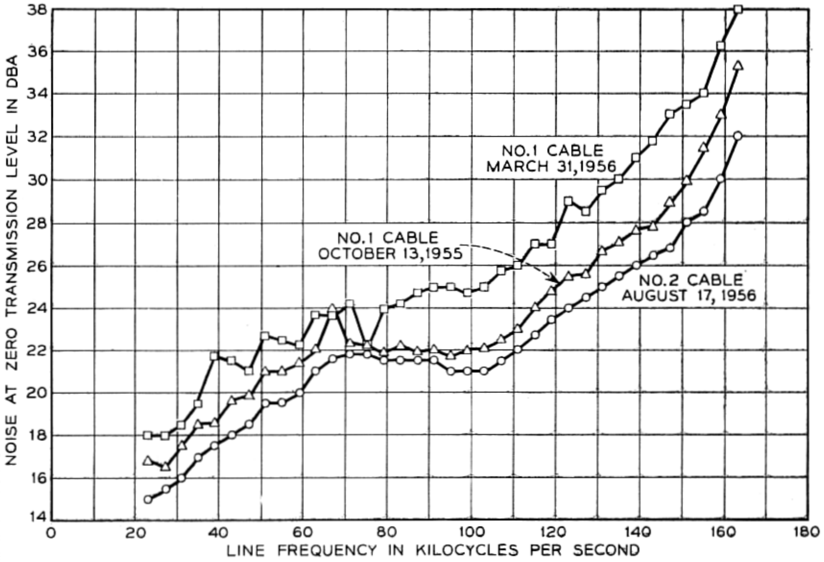

Fig. 16 — System noise.

completion of laying. The noise is lower than on the No. 1 cable. This is because results of experience on the No. 1 cable were utilized in better choice of cable repeater section lengths and in better equalization while laying the 1956 cable.

Modulation Tests

Two-tone modulation tests of second and third order products were made, using a large number of successive frequency combinations. The highest level modulation products were at least 60 db below the 1-milliwatt test tones, at zero transmission level. This is approximately the value computed before the system was laid. Most of the modulation products were down substantially more than 60 db. Probably various causes contributed to the good performance, including the effect of misalignment in lowering repeater levels, and small propagation-time differences which minimize in-phase addition of third-order products from successive repeaters.

Telegraph Transmission Tests

At present writing, telegraph tests have been made only on the printer (telegraph order wire) channels, and without a system multi-channel load. With the proposed specific telegraph level (STL) of −30 db (i.e. telegraph signal of −30 dbm per telegraph channel at 0 db telephone transmission level), the telegraph distortion was too low to measure reliably; it was possible to send clear messages under test conditions with a signal 36 db weaker than this.

Crystal Tests

All of the peaks of noise at the crystal resonance frequencies were easily discernible.

The crystal gain values all lay in the range from 23.6 to 27.2 db, with 60 per cent of them lying in the range from 25 to 26 db. Crystal gain, as used here, is the difference between the system gain at a repeater crystal frequency and the average of the gains at 50 cycles above and below this frequency; the latter value is approximately the gain if the crystal were absent. No significant changes in crystal gain have occurred in eleven months of system life, and none were expected. These measurements are to be continued over the years, as an indication of electron tube aging, as explained in the companion paper on the repeater.[3]

A series of measurements of the frequency of each of the 51 repeater crystals versus time has been made. (Any of these frequency determinations can be checked on the same day within ±0.1 cycle with the special test apparatus and techniques used.) The crystals were designed to be extremely stable in frequency, so that measurements on one repeater, made at the land terminal, would not be affected by the combined effect of 50 other crystals at 100-cycle spacings. The crystal frequency varies only about $-\frac{1}{2}$ cycle per degree Fahrenheit increase in sea-bottom

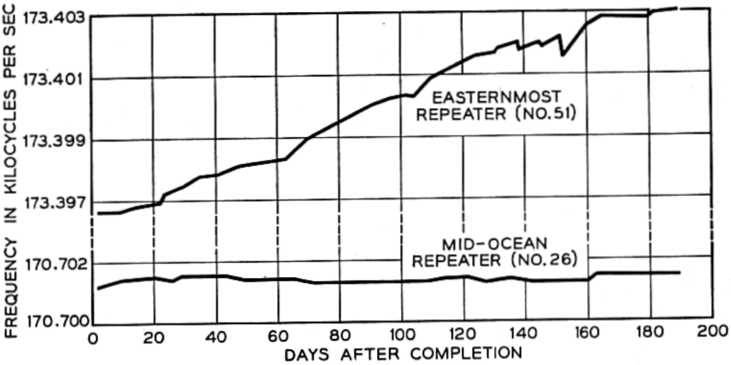

Fig. 17 — Resonant frequency versus time — shore and deep sea crystals.

temperature. The change in frequency due to crystal aging in 11 months under the sea is considered to lie in the range 0 to -0.4 cycle.

Although the crystals were not designed as sea-bottom temperature indicators and are within a repeater housing, it seems likely that with precise techniques and, after some further stabilization, some uniquely accurate information on change of sea-bottom temperature will be obtainable.

In accordance with previous oceanographic knowledge of sea-bottom temperature, the frequency changes have been larger in the crystals near shore. The greatest change has been in the repeater nearest Oban. This is about 17 miles from shore and in water only about 50 fathoms deep. Its frequency change, and that of a typical deep-sea repeater, are shown in Fig. 17.

FUTURE CONSIDERATIONS

Spare Equipment for Cable Stations

In a system as far-flung geographically as this one, and as important, much thought must be given not only to the supplies needed for routine replacement of expendable items, but also to major replacements necessitated by fire or other causes. Accordingly, a schedule of spare equipment has been established, divided into two groups — "shelf" and "casualty".

Shelf spares are carried in the station itself, and include items such as dial lights, electron tubes and dry cell batteries, which have limited life in normal service. These are maintained in the cable station in quantity estimated as adequate for two years of operation.

Casualty spares embrace those major, essential frames and equipments without which the system cannot be operated. There are two subdivisions: those which are in common use in the telephone plant and are, therefore, available by "cannibalization", and those which are special to the project, like the cable current supplies and the cable terminating bays. The common-use items are not stocked as casualty spares. Spares of the special items have been built and are stored in locations remote from the cable stations. In event of catastrophe, these can be drawn out and flown as near the point of need as possible, for onward-shipment by available means.

Spare Equipment for the Undersea Link

Although every effort has been made to produce a trouble-free system, the underwater link is still subject to the hazards of trawlers, icebergs, anchors and submarine earthquakes or land slides. There must be considered, too, the possibility of fault from human failure.

So it is necessary to contemplate the replacement of a length of cable, or a repeater or equalizer. For such contingency, spare cable of the various armor types has been stored on both sides of the Atlantic. Spare repeaters and equalizers are also available.

In addition, a spare called a "repair repeater" has been stocked. Need for this arises from the fact that except in very shallow water, a repair cannot be effected without the addition of cable over and above the length which was in the circuit initially. The amount of cable which must be added is a function of water depth, condition of the sea at the time of the repair, and the amount of cable slack available in the immediate vicinity of the point in question.

When excess cable is introduced in amount sufficient to significantly reduce the system operating margins, its loss must be compensated. Hence, the repair repeater.

A repair repeater is a two-tube device, essentially like a regular repeater although its impedances are designed to match the cable impedances at input and output ends. However, its gain is sufficient to offset only about 5.3 miles of cable. A second type of repair repeater is under consideration, to compensate for about 15 miles of cable.

Long-Term Aging

General

In a system with some 3,200-db gross loss at its top frequency between points which are accessible for adjustment, a long-term change in loss of only one per cent would have a profound effect on system performance.

For this reason, the repeater design included careful consideration of net gain change over the years.[3] The degree of control over aging is such that in a period of at least 20 years, and perhaps much longer, the estimated change in 51 repeaters might total 8 db added gain at the top frequency. The gain variation with frequency would be proportional to either curve of Fig. 15, and the rate of aging would be slower in earlier than in later years.

Estimates of cable aging are discussed in the section on "Net Loss Tests."

Means of Combatting Aging

The effects of aging would become important on the top channels first. Remedial measures to improve signal-to-noise, especially in the top channels, include: possible increase of transmission level at input of the final transmitting and load limiting amplifier in the transmitting terminal; pre-distortion ahead of this amplifier; compandors; increase of dc current; and undersea re-equalization in later years. This last would be very expensive, and so it is necessary to examine fully the possibilities of the other measures.

The penalty for increasing the transmission level at the input of the transmitting amplifier is more peak-chopping and modulation-noise peaks. The improvement that could be realized in this way is probably fairly small.

Pre-distortion is accomplished by inserting ahead of the transmitting amplifier a suitable shaping network adjusted for gain in the top part of the band and loss at lower frequencies. A complementary network (restoring network) is placed at the receiving terminal. This measure would improve signal-to-noise in the uppermost part of the band and reduce it in lower channels which have less noise. Some 3-db improvement might be thus realized in the top channel.

Compandors would give an effective signal-to-noise improvement of up to about 15 db for message telephone service, but none for services such as voice-frequency telegraph. Compandors would be applied only to those channels needing them. They halve the range of talker volume, but also double the transmission variations between compressor and expandor, and thus tend to require some increase in the overall channel net loss. The program (music) channels are already equipped with compandors which use up a part of the obtainable advantage.

If the combination of such measures netted an effective message signal-to-noise improvement of 20 db in the top channel, this would counterbalance aging of some 28 db in this channel, if the aging were uniformly distributed along the system length. Thus considerable aging could be handled without undersea modification.

ACKNOWLEDGEMENTS

A system of the complexity of the one described obviously results from teamwork by a very large number of individuals. However, no paper on this subject could be written without acknowledgement to Dr. O. E. Buckley and J. J. Gilbert and O. B. Jacobs, now retired from Bell Telephone Laboratories. All of the early and fundamental Bell System work on repeatered submarine cable systems, and the concept of the flexible repeater, came from these sources and from their co-workers. Messrs. Gilbert and Jacobs have also contributed to the present project.

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